TITLE:
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CITATION:
Lin, I ...[et al]. DYNAMICAL BEHAVIORS OF COULOMB CRYSTALS AND LIQUIDS IN STRONGLY COUPLED DUSTY PLASMAS(Session II : Chaos, The 1st Tohwa University International Meeting on Statistical Physics Theories, Experiments and Computer Simulations). 物 ...

ISSUE DATE:
1996-06-20

URL:
http://hdl.handle.net/2433/95815

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DYNAMICAL BEHAVIORS OF COULOMB CRYSTALS AND LIQUIDS IN STRONGLY COUPLED DUSTY PLASMAS

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We experimentally study the microscopic dynamical behaviors of the strongly coupled dusty plasma with SiO_2 suspensions in low pressure rf Ar discharge through optically tracing the trajectories of particles. As rf power increases, the large scale cooperative domain motion and rotation, cyclic hopping, defect motion and interaction, and diffusive type motion are excited and observed.

Dusty plasma is a system with fine particle suspensions in a plasma background [1]. The large amount of negative charges on particles induced by the large electron mobility in the plasma increase the degree of Coulomb coupling by serveral orders of magnitude [1,2]. Following the theoretical predition by Ikezi [3], the formation of Coulomb crystals and liquids with submillimeter interparticle distance have been demonstrated by our recent experimental studies [4-6] and the formation of 3D and 2D solids have also been studied by other groups [7,8]. Namely, the presence of dust particles extends the gasous plasma to the strongly coupled regime. The microscopic structure and dynamical behaviors can be optically monitored.

For a many body Coulomb system, the interplay between the Coulomb coupling and thermal excitation induces interesting dynamical behaviors. Unfortunately, only few systems with large scales, such as the liquids with the colloidal suspensions, allow direct optical observation [9]. Unlike the highly viscous liquid background of the above system, which usually overdamps the particle motion, the dusty plasma system exhibits richer microscopic phenomena becuause of the higher particle mobility in the low pressure plasma background. In this paper, we present our experimental observation of the microscopic dynamical behavior from the ordered hexagonal crystal to the disordered liquid state.

The experiment is conducted in a novel annular rf dusty plasma trap described elsewhere [4]. It consists of a hollow outer electrode capacitively coupled to a 14 MHz rf power amplifier, a gounded center electrode with an annular groove for particle trapping, and a top glass window for observation. The micron size SiO_2 particles are generated through gas phase reaction between the silane and oxygen gases in the low pressure Ar discharge. The degree of Coulomb coupling decreases monotonically with increasing rf power. Particle motion are monitored through an optical microscope with optical axis parallel to the gravitational field. In this work, we choose the hexagonal system. For this quasi 2D structure, particle motion remains only on the horizontal focus plane and can be easily monitored. Why the hexagonal structure can be a stable structure is not the issue of this work.

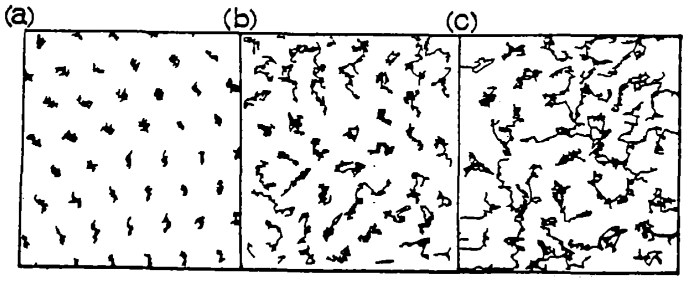

Fig. 1. (a) The 5 sec trjectories of the hexagonal state. (b) and (c) The 3 sec trajectories of the liquid states with increasing rf power.

Fig. 1 shows the particle trajectories of different states with finite exposure times as rf power increases. Fig. 1 a corresponds to the highly ordered hexagonal crystal state, in which the particles only move slightly around their equilibrium positions. The state has good translational and orientational orders. At higher rf power (Fig. 1 b), the system turns into the liquid state. The particle mean square displacement increases. Although the system loses its long range order, each particle is still surrounded by six nearest neighbors. Sometimes, thermally induced hoppings can be observed. At higher rf power (Fig. 1 c), hopping becomes more frequent and it corresponds to a hotter liquid state.

Fig. 2 shows the sequential evolution of the microscopic state before melting at a fixed rf power. In general, crystal domains with different sizes and relative motions are observed. Particles in the same domain behave collectively. Some of the domains rotate and some of them are stationary in a short period about a few seconds. The relative motion causes strong shears around the domain boundary, which usually induces large stress. For example, in Fig. 2a, the domain in the upper left corner rotates clockwisely, while the particles outside the domain and adjacent to the dashed line move oppositely. The local adjustment of particles around the domain boundary can change the size and shape of domains. Namely, the collective excitations have finite life time. No region is really pinned even sometimes it is stationary in a short period.

The collective excitation has different scales. The system can run into a state with smaller vortices (Fig. 2 c), which corresponds to poor translational and orientational order. Cyclic hoppings similar to those obtained through the computer simulation can be easily observed [10]. The vortex with cyclic hopping dispear after the particles hop to their adjacent sites and other vortices can then be generated in other places. The system can sometimes reenter a microscopic state with excellent translation and orientation order similar to the cold crystals shown in Fig. 1 a.

The thermal excitation of domains with relative motion generates strong shear and distorts the lattice. The order of the system can be described by "defect" through the triangulation process [9]. For example, Fig. 3 shows the sequential evolution of a typical recombination process of free dislocation (FD) defects. Each FD has a bound pair of fivefold and sevenfold cells and a pair of extra lattice lines intersecting at the center of the 5-fold cell. It is found that the FD moves along the Burgers vector (BV) normal to the 5-7 bond. FD A and B are accelerated and then recombine into FD C. The overall BV is a conserved quantity in the recombination process, e.g. the BV of C equals the sum of the BV of A and B in the above process.

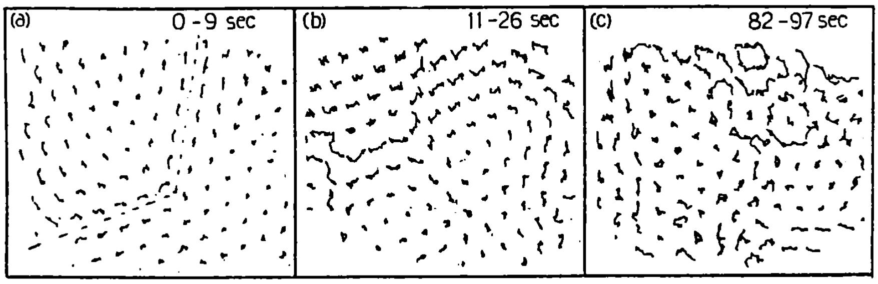

Fig. 2. The sequential evolution of the microstate around melting at a fix rf power with different exposure time (sec).

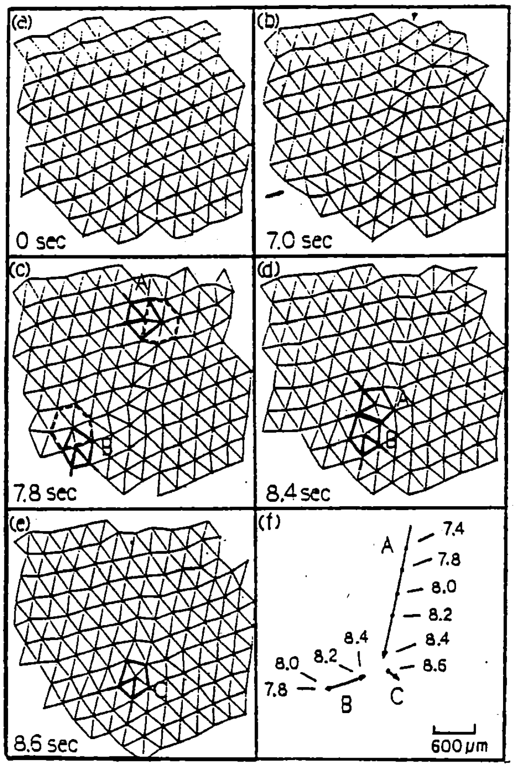

Fig. 3. The state evolution showing the cooperative motion induced kinks, and the acceleration and recombination of FDs. The five fold cells, the extra lines, and the 5-7 bonds of FDs are marked (The seven fold cells are also marked in (c). (f) The trajectories of the center of the 5-7 bonds for the recombination process at different time (in sec). The arrows indicate the directions of the FD motion.

Other than the recombination process, we also observe the pair generation and annihiliation of FDs with opposite BVs, and the dissociation of a single FD into a pair of FDs with BV angle around 120°. As the system enters a state similar to Fig. 2d, the system has relatively higher FD density and shorter FD life time. Actually, FDs are produced through the pair generation and dissociation processes, propagating along the shear direction , interacting with each other and destroyed through the recombination and annihilation processes. Namely, the system around melting can be treated as a strongly coupled FD gas system. This is very similar to the hexatic state predicted by the KTHNY theory [9,11-13], which gradually loses its translational order in a two stage melting process of a thermal equilibrium 2D hexagonal lattice. Note that our system is a nonequilibrium system. The details of defect dynamics are reported elsewhere [14].

We have also measured the mean square displacement (MSD) of particles in the liquid state. For particle diffusion, the general scaling law, MSD t^{2H} is followed [15]. It is found that, as the system becomes hotter, H increases and gets closer to 0.5 which is similar to the value for a random walk process. It is interesting to point out that, if we calculate the MSD relative to the center of mass of a cell containing the particle and its six surrounding neighbors, H is less than o.5. Namely, the interaction with the neighboring particles makes the motion anticorrelated (or anti-persistent). The particle feels the repulsive force from the surrounding particles when it moves away from the center of mass position.

In summary, we have investigated the dynamical behaviors of particles in the dusty plasma crystal and liquid. The competition between the Coulomb coupling and thermal fluctuation leads to the decrease of correlation length as the rf power increases. The thermally induced cooperative excitations from the large scale domain motion to the small scale cyclic hopping associated with interesting defect phenomena have been observed. In the liquid phase the system still has short range correlation which is the source for the anitcorrelated diffusive motion .

This work is supported by the National Science Council of R.O.C. under contract No. NSC-85-2112-M008-011.

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